Classification of RF transients in space using digital signal processing and neural network techniques

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ABSTRACT

The FORTE' (Fast On-Orbit Recording of Transient Events) small satellite experiment scheduled for launch in October, 1995 will attempt to measure and classify electromagnetic transients as sensed from space.The FORTE' payload will employ an Event Classifier to perform onboard classification of radio frequency transients from terrestrial sources such as lightning. These transients are often dominated by a constantly changing assortment of man-made "clutter" such as TV, FM, and radar signals. The FORTE' Event Classifier, or EC, uses specialized hardware to implement various signal processing and neural network algorithms. The resulting system can process and classify digitized records of several thousand samples onboard the spacecraft at rates of about a second per record. In addition to reducing dowlink rates, the EC minimizes command uplink data by normally using uploaded algorithm sequences rather than full code modules (although it is possible for full code modules to be uploaded from the ground). The FORTE' Event Classifier experiment combines science and engineering in an evolutionary step toward useful and robust adaptive processing systems in space.

1. INTRODUCTION

The FORTE' (Fast On-Orbit Recording of Transient Events) mission is a United States of America Department of Energy small satellite experiment scheduled for launch in late 1995. The payload is designed to measure radio frequency (RF) electromagnetic transients and associated optical signatures that emanate from below the Earth's ionosphere. Los Alamos National Laboratory is responsible for this mission, with key subsystems supplied by Sandia National Laboratory and private industry. The proposed 68^{o} inclination circular orbit at an altitude of 800 km will place the payload above the ionosphere. The payload is designed to function in a highly variable natural radiation environment that produces roughly 5 krads radiation dose over the anticipated one year duration.

Novel satellite features include a composite spacecraft structure, CCD and photodiode optical detectors, a 30 to 300 MHz RF system composed of a 10 m crossed log periodic antenna array coupled to state-of-the-art analog and high speed analog-to-digital electronics, an onboard event classifier, and a modern ground station. Both optical and RF data will be telemetered to the ground during the course of this experiment, but the RF data will also be classified onboard by the event classifier. The system requirements, scientific constraints, subsequent design and implementation, and known limitations of the FORTE' RF event classifier are the topics of this paper.

2. EVENT CLASSIFIER REQUIREMENTS

The Department of Energy is currently investigating economical and reliable techniques for space-based nuclear weapon treaty verification. Nuclear weapon detonations produce RF transients that are signatures of illegal nuclear weapons tests. However, there are many other sources of RF signals, both natural and man-made. Direct digitization of RF signals requires rates of 300 MSamples per second. Such digitization produces on the order of 10^{13} samples per day of data to analyze. It is impractical to store and downlink all digitized RF data from such a satellite without a prohibitively expensive increase in the number and capacities of ground stations. Reliable and robust data processing and information extraction must be performed onboard the spacecraft in order to reduce downlinked data to a reasonable volume. This processing must be performed in an environment that includes both external and internal sources of errors and noise. The FORTE' event classifier, or EC, represents an evolutionary step toward such advanced onboard satellite data processing and reduction.

Although direct classification of RF signals as they are received in space is not feasible with current technology, by using RF and optical triggers to reduce the event rate, digitization and processing in a store-and-forward system is possible. However, even with advanced triggering schemes, multiple triggers from sources such as mesoscale lightning storms can fill the 160 MByte payload memory with digital event records in as quickly as a second. These is still an unacceptably high data rate. The goal of the FORTE' EC is to integrate enough onboard digital signal processing into this sophisticated store-and-forward digital system to further reduce the data stream to a manageable downlink rate.

Because we cannot predict the exact RF signatures of an illegal nuclear event, because the RF background in space is not well characterized, and because techniques for classifying these signals are constantly evolving, the EC experiment must be flexible and reconfigurable. In addition, the EC must be adaptive because both the background "clutter" and the ionosphere (and its attendant effects) are highly variable. The possibilty of component failures due to the hazardous natural environment requires that the EC be robust. Finally, the EC size, weight, power, and cost impacts on the system must be minimized.

As a result of these requirements, the Event Classifier has been designed into the FORTE' payload as shown in Fig. 1. The EC is connected only to the Flight Payload Controller (FPC). The FPC turns on the EC only when it is needed by enabling power to the EC. The FPC routes commands to the EC over a 9600 Baud serial link and sends digitized records over a 16 bit bidirectional parallel link clocked at rates up to 6 Mhz. The EC returns record classifications back to the FPC over the parallel link. Returning record classifications of a few bytes rather than full digitized records of 10^3 to 10^4 bytes reduces onboard storage and downlink requirements to manageable values.

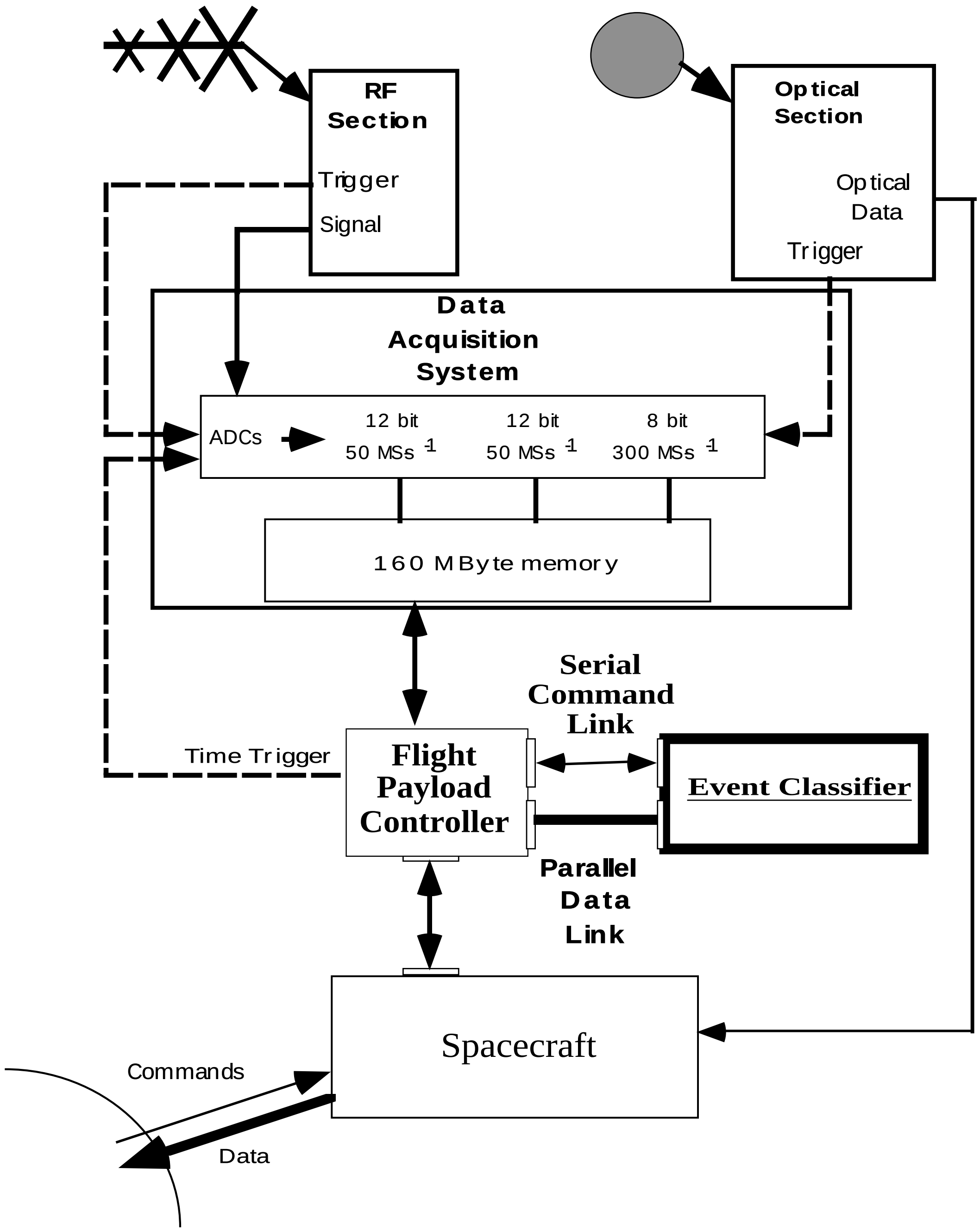

Figure 1. Functional diagram of the FORTE' experiment. The Data Acquisition System can be triggered by an RF trigger, an optical trigger, or by the Flight Payload Controller at preset times. The Flight Payload Controller routes commands (via serial link) and RF data records (via parallel link) to the Event Classifier. This Event Classifier classifies RF transients that meet trigger criteria.

The EC is an experiment to determine the feasiblity of telemetry reduction by onboard classification. The EC experiment will proceed in three steps. First, processing and classification algorithms will be applied to digitized waveforms downlinked by the FORTE payload through the ground station to desktop computers. Next, promising algorithms will be tested in the FORTE engineering unit on the ground. Finally, after successful ground testing, the EC will then be commanded to perform the same analysis in space. Successful demonstration of onboard event classification by the EC will establish confidence limits of classifications and enable follow-on missions to eliminate the costly data downlink and ground analysis steps.

3. SCIENTIFIC BACKGROUND

The RF environment in space is dominated by man-made signals including continuous wave TV and radio carriers and short-term signals from a variety of communication and radar transmitters. However, the RF environment in space also includes various transient signals. Some transients are produced by local mechanisms such as spacecraft discharges. Other transients are produced by naturally occurring broadband and impulsive sources such as lightning. Panel (a) in Fig. 2 is a synthesized time series produced by a broadband impulsive source.

The ionosphere induces frequency-dependent dispersion for all RF signals that pass through it[1]. Higher frequencies travel faster than lower frequencies, causing impulsive signals to spread out in time. This effect can be modeled as:

$$t - t_0 = c/f^2 \qquad (1)$$

where t is time, t_0 is the speed of light travel time from the source to the observer, f is frequency, and c is a constant[1]. Panel (b) of Fig. 2 shows the effect of this ionospheric dispersion on the source signal in the top left panel.

Fig. 2(b) illustrates that ionospheric dispersion lowers the signal-to-noise ratio of broadband impulsive RF signals in the amplitude vs. time domain that is directly sensed by the RF system. The instantaneous signal-to-noise ratio can be improved by transforming the time series into a 2-D image of power as a function of frequency vs. time. The results of this transformation are shown in Panels (c) and (d) of Fig. 2. These lower panels are the power spectral density estimates obtained via short term Fourier transform from the signals shown directly above them.

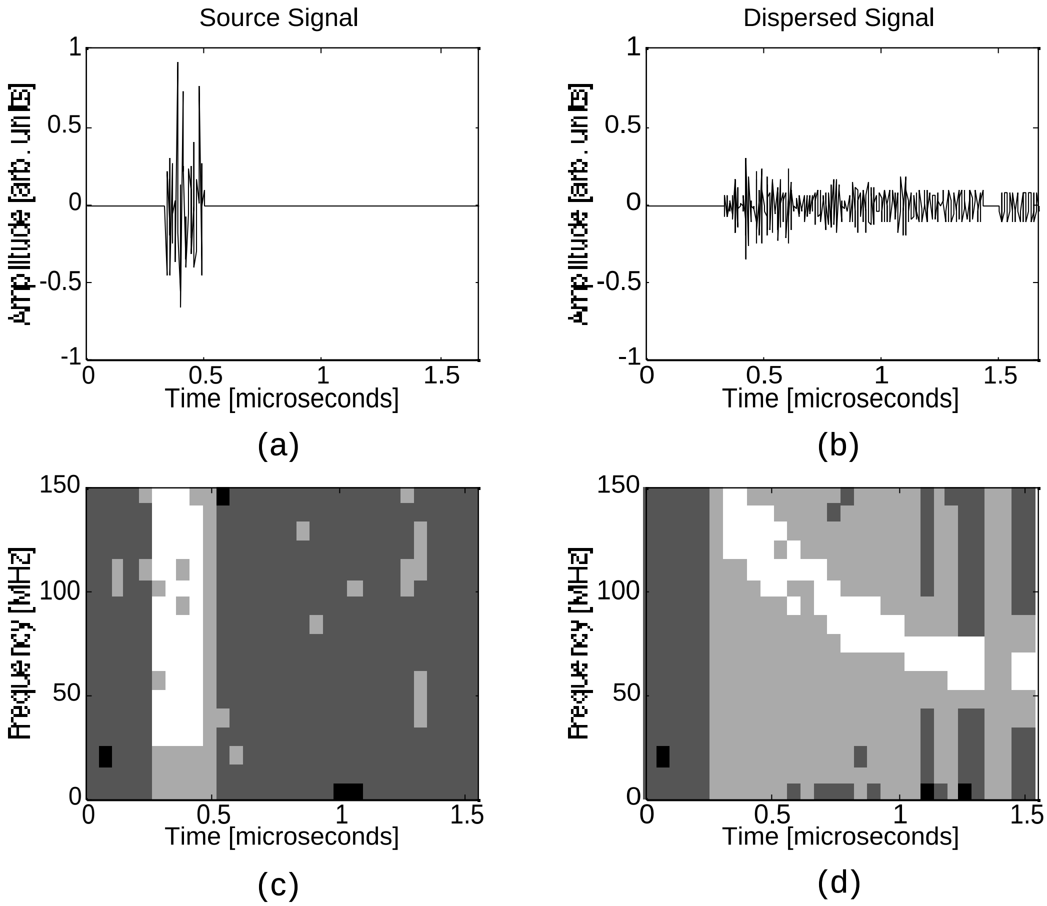

Figure 2. Synthetic time series and power spectral density representations of a broadband impulsive source signal and that same signal ionospherically dispersed. Panel (a) is a waveform constructed from 21 frequencies, all with equal amplitude and random phase, evenly spaced between 30 and 300 MHz. Amplitudes are in arbitrary units. Panel (b) is the source time series dispersed by a simplified model of the ionosphere (Eq. 1). Panels (c) and (d) show the joint frequency-time spectrograms produced by a sliding Fourier transforms (a sliding window of 32 points, shifted by 16 points each time) over the time series in panels (a) and (b), respectively. This Figure illustrates that although dispersion lowers the signal-to-noise ratio in the time series, the instantaneous signal-to-noise ratio of the dispersed signal is effectively restored by power spectral density estimation.

The dispersion in Figs. 2(a) and 2(d) is due only to the model ionosphere. The source information is encoded into other parameters such as curve width and power as a function of frequency along the curve. Fig. 3 schematically shows the currently identified space-sensed RF signal types in a power spectral density representation. Transients can be selected on the basis of their ionospherically-induced dispersed (curved) shapes, but classification of the transients must be performed on features other than the shape of the curve. If the ionospheric conditions along the signal path are sufficiently known, the dispersed signal can be inverse dispersively filtered, or dechirped, to obtain the source signal over a limited bandwidth; however, ionospheric conditions are not typically well known and numerical dechirping is often unstable. Thus, classification of known and unknown transient signals from sources with unpredictable characterictics must be performed in a frequency dispersed representation where the degree of dispersion is highly variable and not independently determined.

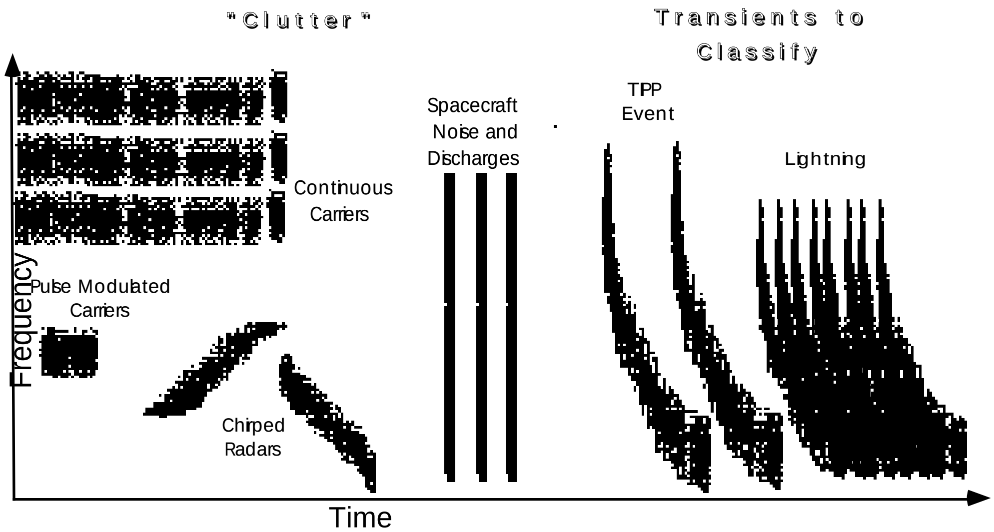

Figure 3. Schematic representation of the power spectral shapes of reported RF waveforms as sensed from space. The ionosphere significantly alters RF signals from terrestrial sources by inducing a frequency-dependent dispersion proportional to the ionospheric total electron content along the frequency-dependent raypath from the source to the space receiver. The FORTE' analog RF trigger is designed to select and capture only the transients. Classification into lightning, transionospheric pulse pair (TIPP) event, etc. is provided by the Event Classifier.

Lightning is a source of naturally occurring broadband impulsive transients observed from space. Lightning science is currently an active area of research. The physical processes responsible for producing the optical and RF signatures in cloud-to-cloud and cloud-to-ground lightning are believed to be different. The relatively slow (10^{-6} s) optical flash is produced chiefly by the return stroke of the lightning process. The low-frequency (10 - 30 MHz) RF signature is also chiefly produced by the return stroke[2,3]. The 30 to 300 MHz transients are believed to result from the lightning leader and intracloud processes[4,5] These higher frequencies correspond to time scales of $3x10^{-8}$ to $3x10^{-9}$ s and imply length scales of 10 m to 1 m (at the speed of light). Experimental observations of electron avalanche breakdown time scales in air[6,7] roughly agree with these values. A primary FORTE' mission science goal is to develop a comprehensive understanding of the correlation between the optical flash and the RF emissions from lightning.

4. EVENT CLASSIFIER IMPLEMENTATION

The requirements for flexibility, reconfigurability, adaptivity, robustness, and cost minimization in the EC are currently best addressed by digital signal processing followed by neural network classification. However, the present generation of neural network hardware is not sufficiently resistant to the natural radiation environment in space to meet mission requirements. Because both the digital signal processing algorithms and the feed-forward neural classification schemes currently envisioned for the EC rely heavily on multiply-and-accumulate operations, the best present engineering choice for the EC is specialized digital signal processing (DSP) hardware optimized for multiply-and-accumulate operations and radiation hardened to meet mission requirements.

The first EC design incorporated a commercially available Versa Modular Eurocard (VME) module with 4 Texas Instruments TMS320C40 DSPs and 10 MBytes of memory[8]. This hardware was determined to be have an unacceptably high radiation-induced failure rate over the anticipated mission orbit. A subsequent redesign has been documented[9]. This custom system is optimized for low weight and power yet high speed and radiation tolerance. This design incorporates a single Texas Instruments TMS320C30, a radiation-hardened Intel 80C31 microprocessor, an Actel programmable gate array, and various types of memory chips with varying degrees of radiation susceptibility. The EC electrical design is shown schematically in Fig. 4.

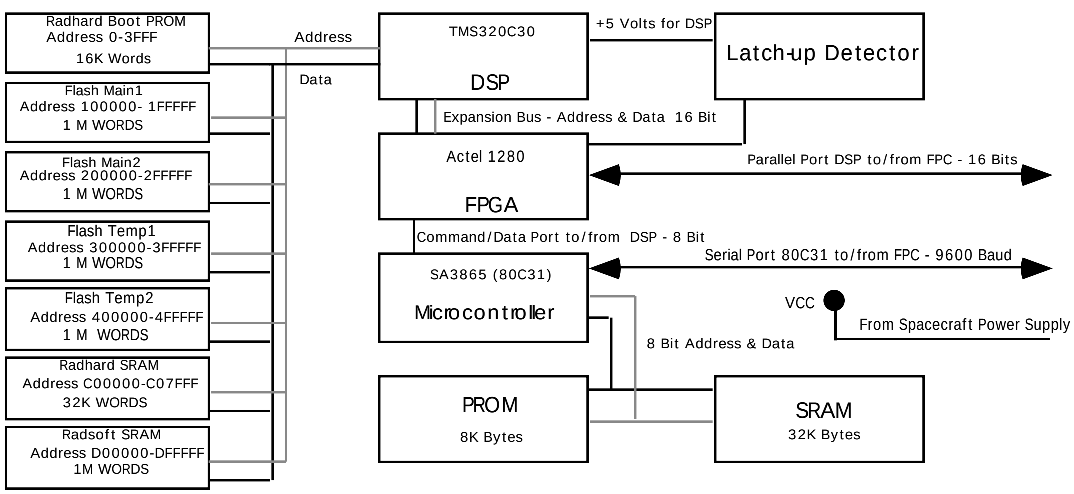

Figure 4. The FORTE' EC electrical design[9,10]. The C30 DSP performs the computations for the signal preprocessing and classification. The DSP is constantly monitored both in hardware and software for radiation-induced latchups. The radiation-hardened microcontroller provides a stable interface to the FORTE Flight Payload Controller and supervises the operation of the C30. The programmable gate array is an efficient method for implementing both external and internal interface circuitry. The use of multiple types of memory chips maximizes available memory while minimizing the expenses and limitations of radiation-hardened memory.

The EC mechanically consists of two 6x9 inch rectangular circuit boards. Each assembled board is placed horizontally into a perimeter aluminum box frame with a reinforcing center rib. After top and bottom horizontal box cover plates are secured by screws, two flexible circuit board interconnections are installed and the electrically connected boxes are placed one on top of the other inside a final aluminum assembly box. This final assembly box is then secured horizontally to the top payload deck of the composite spacecraft structure. The final EC assembly weighs 5 kg and provides 0.080 inches of aluminum shielding.

The EC is connected to the raw, unregulated, nominal 28 Volts DC spacecraft power. Power converters in the EC assembly convert this raw spacecraft power to the +/-12 Volt and + 5 Volt levels required by the EC electronics. The FPC controls whether the EC is on or off by toggling the inhibit signal to these EC power converters. The EC draws no power in the off state and 5 Watts in the on state. The FPC monitors for gross malfunctions of the EC by sending housekeeping requests (via the serial link) to the EC once a second and cycling the EC power if the EC fails to respond.

The primary sources of natural radiation capable of affecting electronics operations during the proposed FORTE' mission in low-Earth orbit are geomagnetically trapped plasma particles (primarily protons and electrons, but also including singly ionized oxygen ions) and energetic particles produced during solar disturbances that are injected into the Earth's magnetosphere. Current models[11] of the space environment predict that the FORTE' components must withstand a total mission dose of 5 kRads.

The C30 DSP can withstand a total dose of about 5 kRads[12] but is susceptible to destructive latchup. The EC structural frame is predicted[11] to reduce the anticipated C30 latchup and single-event upset rates due to penetrating particles to insignificant levels during normal environmental conditions. However, latchups and upsets are anticipated over the South Atlantic geomagnetic anomaly and during bursts of very energetic particles associated with solar disturbances. The EC must provide a generally reliable and stable interface to the FPC, so the EC design in Fig. 4 uses a radiation-hardened Intel 80C31 microcontroller as the primary controller and the potentially unreliable C30 as an analysis coprocessor.

The EC has three levels of protection against destructive latchups of the C30. First, a hardware reset circuit disables the C30 when the power consumption exceeds a trip point (1, 2, 3, or 4 Watts) commanded by the 80C31 microcontroller. Second, the 80C31 microcontroller disables the C30 when it receives an interrupt from a hardware watchdog timer circuit. The C30 must reset the watchdog timer roughly once a second; if it fails to do so, this interrupt is generated. Third, the 80C31 microcontroller disables the C30 when the C30 supply voltage is abnormal. The C30 supply voltage is provided by a register that is constantly updated by a voltage to frequency converter.

The EC employs an Actel programmable gate array. This device is programmed to provide all interfaces between the 80C31, the FPC parallel port, and the C30. It provides command and status registers, memory address decoding, interrupt generation, latch detect cicuitry, and watch dog timers in a high density but low power radiation-hardened form. This technology is highly and easily reconfigurable and has enabled design and fabrication errors to be corrected without expensive redesign, acquisition of new or different components, and refabrication of circuit boards.

Different types of memory are used in the EC because the time scales (and hence radiation resistance) for storage of boot codes, uploadable algorithms and results, and executing code and temporary data are different. Costs and execution times have been minimized by judicious use of radiation-hardened memory. Only the boot codes are stored in radiation hardened programmable read only memory (PROM). The 80C31 has 8 KBytes of boot PROM and 32 KBytes of radiation hardened static random access memory (SRAM). The C30 has 64 KBytes of boot PROM, 16 MBytes of flash electrically eraseable PROMs (EEPROMs) for algorithms and result storage, 128 KBytes of radiation hardened SRAM for stack memory, and 4 MBytes of radiation susceptible SRAM for scratch memory.

After the FPC turns on the EC by enabling the EC power converters, both the 80C31 control microprocessor and the C30 DSP execute boot sequences that initialize both the individual processors and the interprocessor communications. At this point, the 80C31 microprocessor software has two main tasks. The first task is to monitor the operation of the C30 and respond appropriately to the 1 HZ FPC housekeeping requests (used by the FPC to determine the current status of the EC). The second task is to receive all commands from the FPC and either process these commands directly or pass them to the C30.

These commands notify the C30 to accept a new algorithm sequence, start analysis of data, download data analysis results, or accept upload of new algorithm codes. The EC uses algorithm sequences rather than full code to minimize command uplink requirements while maximizing reconfigurability. For example, by storing two different software triggers (algorithms 1 and 2), two different power spectral density estimation routines (algorithms 3 and 4), and three different classifiers (algorithms 5, 6, and 7) in the EC, only the number sequence (e.g., 1-4-6, and supporting parameters) need be uplinked. New algorithms can be uploaded to the EC, but only the individual new code modules need be uplinked.

5. DISCUSSION

The Event Classifier will have a variety of preprocessing and neural net options programmed onboard. The current baseline algorithm sequence for the initial spacecraft orbits is a multiband trigger for region-of-interest extraction, a short term Fourier transform for power spectral density estimation, and a self-organizing map neural network for unsupervised classification. If initial classification results indicate that an adequate training set can be constructed, supervised feed-forward neural techniques such as backpropagation will be tried as classifiers.

The FORTE' mission will study RF transients from terrestrial sources. One way for a spacecraft to sort terrestrial RF transient sources from all the clutter is to look for transients that have been dispersed by the ionosphere. The baseline EC algorithm uses a multiband trigger to select dispersed RF transients for subsequent classification. This multiband trigger monitors power in multiple center frequency narrow bandwidth channels. A band trigger is generated when the power in that band exceeds a given amplitude. A multiband trigger occurs when a specified fraction of band triggers with a specified temporal sequence occur. Such a trigger can select ionospherically dispersed transients if appropriate frequencies, bandwidths, band trigger power level thresholds, and temporal relationships specified. However, this is equivalent to specifying the ionospheric dispersion due to a non-uniform and time-varying ionosphere on defined "signals" emanating from any RF source within the antenna field-of-view; i.e., this trigger must adapt over the course of the spacecraft orbit. Significant effort will go into implementing and optimizing such an adaptive trigger during the EC experiment.

Classification is simplified by the proper choice of feature space. The baseline EC algorithm sequence uses estimated "instantaneous" frequency as this feature space. The short term Fourier transform has proven to work satisfactorily for human classification. We previously reported[8] that transients, carriers, and noise are effectively distinguished by a self-organizing map when the power spectral density spectrograms are used as inputs. We have recently used the same technique on actual space data to distinguish TIPP events from transients produced by a ground-based RF pulser. A disadvantage of this technique is the large number of inputs and hence neural network complexity that results; several tens of frequency bins and time intervals results in hundreds of inputs. We are currently investigating curve fitting and parameter extraction as preprocessing steps to reduce the number of neural network inputs.

Fourier transforms are only one technique of estimating power spectral density and the power spectral density representation is only one of many possible feature spaces. Research into alternatives to the EC baseline algorithm is underway and, because the EC can be uploaded with new algorithm modules, this research will continue through launch.

In conclusion, the FORTE' mission will provide exciting new information on lightning and ionospheric physics. A key element of this combined RF and optical space-based experiment is the onboard Event Classifier. The goal of the EC is to demonstrate dramatic reductions in satellite downlink requirements by performing intelligent and robust information extraction onboard the spacecraft. This is an important first step in the probable direction of future space mission designs.

The EC is a testbed for data processing and classification techniques such as power spectral density estimation and neural network classification. The EC uses modern modular programming techniques to maximize reliability and minimize system resources. Further, the EC is a space engineering testbed for modern electronic components such as the digital signal processor and the programmable gate array. This latter device can currently be clocked at rates up to 50 MHz. Future improvements are expected to push clock rates above 100 MHz. At these higher speeds, gate arrays can push beyond their current role of providing digital circuit building blocks and into the realm of high speed finite impulse response filters[13] and neural networks[14]. The EC will provide a performance benchmark for these devices in space.

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7. REFERENCES

1. K. G. Budden, The Propagation of Radio Waves, Cambridge University Press, 1985

2. C. E. R. Bruce and R. H. Golde, "The lightning discharge", *J. IEEE*, 88, p. 487, 1941.

3. Y. T. Lin, M. A. Uman, and R. B. Standler, "Lightning return stroke model", *J. Geophys. Res.*, 85, p. 1571, 1980.

4. P. L. Rustan, M. A. Uman, D. G. Childers, W. H. Beasley, and C. L. Lennon, "Lightning source locations from VHF radiation data for a flash at Kennedy Space Center", *J. Geophys. Res.*, 85, p. 4893, 1980.

5. D. E. Proctor, "VHF radio pictures of cloud flashes", *J. Geophys. Res.*, 86, p. 4041, 1981.

6. H. J. White, "Effect of intense illumination on time lag in static spark breakdown", *Phys. Rev.*, 49, p. 507, 1936.

7. R. W. Wilson, "Very short time lag of sparking", *Phys. Rev.*, 50, p. 1082, 1936.

8. K. R. Moore, J. F. Wilkerson, D. Call, S. Johnson, T. Payne, W. Ford, K. Spencer, and C. Baumgart, "A space-based classification for RF transients", *Proceedings of the International Workshop on Artificial Intelligence Applications in Solar-Terrestrial Physics*, Lund, Sweden, 1993, p. 205, pub. by NOAA Space Environment Laboratory, Boulder, Colorado, USA

9. S. Briles, K. Moore, P. Blain, P. Klingner, D. Neagley, M. Caffrey, K. Henneke, and W. Spurgeon, "Innovative use of DSP technology in space: FORTE Event Classifer," *Proc. International Conferrence on Signal Processing Applications and Technology*, Dallas, Texas, Vol. II, p. 1447, 1994.

10. S. Briles, K. Moore, P. Blain, P. Klingner, D. Neagley, M. Caffrey, K. Henneke, and W. Spurgeon, "Studying transient events from space", *Electronic Engineering Times*, 819, p. 40, 1994

11. Space Radiation, Severn Communications Corporation, DOS Version 2.0, 1993

12. P. F. Siy, J. T. Carter, L. R. D'Addario, and D. A. Loeber, "Dose rate and total dose radiation testing of the Texas Instruments TMS320C30 32-bit floating point digital signal processor", MITRE Corporation report ESD-TR-91-215/MTR-11119, 1991

13. Les Mintzer, "Signal Processing With FPGA's", Momemtum Data Systems, 1994

14. "Signal Processing with Xilinx FPGA's And Momentum Data Systems Software", Xilinx, 1994.